THE ANGULAR DISTRIBUTION OF THE NEUTRONS FROM THE D-D REACTION

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Abstract

The angular distribution of the neutrons from the D-D reaction has been investigated at 145 kV and 190 kV by assuming that it is of the form B $(1 + A \cos^2 \theta)$ and determining the value of A. This was done by measuring the intensity of the neutrons with silver cathode Geiger counters at 90° and 0° to the incident deuteron beam. At 145 kV, A was found to be 0·90 and at 190 kV, 1·03; the error in each value being less than 10%. These values lie on the smooth curve for the proton distribution predicted by theory.

Introduction

The D-D reaction gives the two alternative transmutations:

$$D^2 + D^2 \longrightarrow H^3 + H' \quad \ldots \quad (1)$$

$$D^2 + D^2 \longrightarrow He^3 + n' \quad \ldots \quad (2)$$

The angular distribution of the protons from the reaction (1) has been investigated by Neuert (1) in 1937 and by Haxby, Allen and Williams (2) in 1939. On expressing their results in centre of gravity co-ordinates with angles referred to the direction of the deuteron beam, they obtained symmetry about the 90° plane as well as about the 0° axis. This result was to be expected since, in the centre of gravity coordinate system, the deuterons approach one another with equal velocity. The distribution obtained was of the form B $(1 + A \cos^2 \theta')$; A and B being constants and θ' the angle between the direction considered and the incident deuteron beam. Their measurements at 106 kV and 190 kV indicated that A was independent of the accelerating voltage.

However, later work by Huntoon, Ellett, Bayley and Van Allen (3) showed a marked dependence of A on the accelerating voltage in the region below 0·5 MeV.

Since the spins of the neutron and proton are identical and the energy balances in the reactions (1) and (2) of the same order of magnitude, it is highly probable that the angular distribution of the neutrons can be represented by an expression similar to that for the protons.

In 1936 Kempton, Browne and Maasdorp (4) carried out measurements on the neutron distribution from the D-D reaction and found that it could be represented likewise by the expression B $(1 + A \cos^2 \theta)$ but they were unable to detect any dependence of A on the accelerating voltage between 100 kV and 200 kV. Bennett, Mandeville and Richards (5) in 1946 determined A for neutrons, as a function of accelerating voltage above 0·5 MeV and obtained the curve shown in figure (1). This curve, they pointed out, would join smoothly on to the values of A obtained by Huntoon, etc. for the proton distribution and they therefore suggested that for low deuteron energies the values of A for neutrons coincide with those for protons and are voltage dependent. Haxby, Allen and Williams (2) point out that a non-dependence of A on accelerating voltage is not understandable on present theory and it is therefore important to check on the values quoted by Kempton, Browne and Maasdorp.

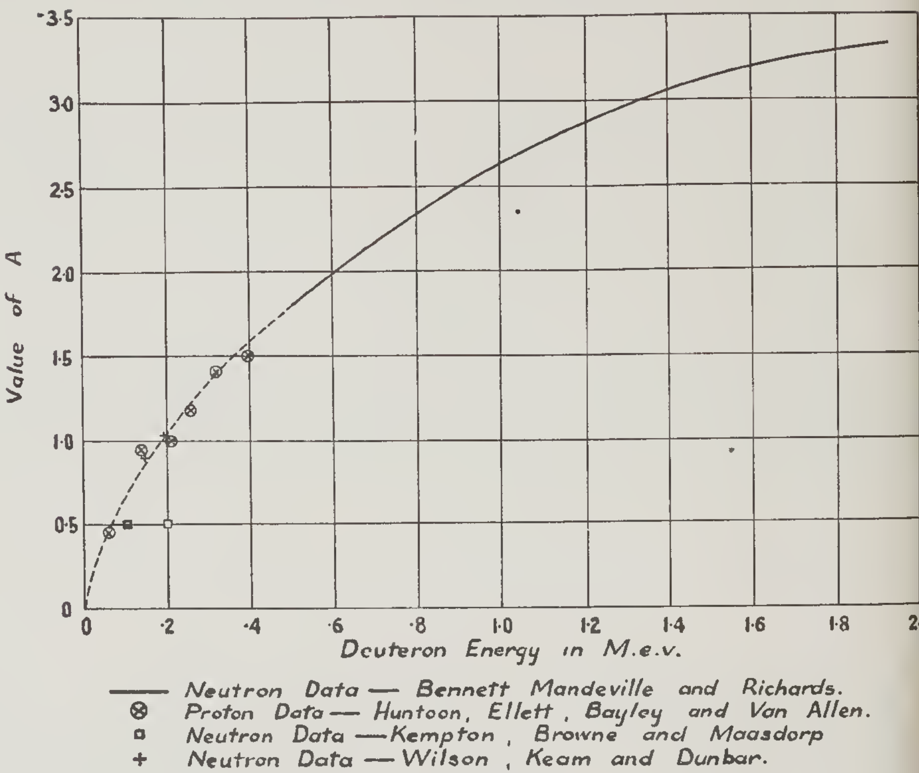

Fig. 1.

Experimental

The D-D source used in the present experiment was a 200 kV neutron generator described by Martin, Hill and Darby (6). The yield of 2-3 curies Radon-Beryllium equivalent obtained from this generator varied critically with the operating conditions and the yields at various angles had to be compared with one another through a monitor count. Thus if I_θ' is the intensity at position 1, when the monitor intensity is I_M', and I_θ'' is the intensity at position 2 when the monitor intensity is I_M'', then

$$\frac{\text{Intensity in Position I}}{\text{Intensity in Position II}} = \frac{I_\theta'}{I_M'} \times \frac{I_M''}{I_\theta''}$$

Ideally, the detector* employed should be sensitive to only the direct neutrons, that is, it should have an energy threshold just below the energy of the slowest neutrons from the reaction. The detector and monitor used were Geiger counters with silver cathodes. Neutrons induce in the silver, activities with half lives of 22 seconds and 2·3 minutes and the β-emission from these radioactive products can be taken as a measure of the incident neutron intensity. Slow neutrons are more effective in inducing radioactivity in silver than are fast ones, thus not only will silver counters detect neutrons of all energies, but their greatest sensitivity will be exhibited to neutrons of thermal velocities scattered onto them, instead of to the fast neutrons coming directly

* Since the monitor is simply to record total yield, it is immaterial whether it detects slow neutrons or not.

from the target. Special measures had therefore to be taken to lessen the sensitivity of the detector to slow neutrons in relation to fast neutrons, and techniques developed to enable the calculation of the background contribution to the measurements. The counters were accordingly enclosed in paraffin cylinders of 8 cm. diameter around which were placed cadmium sheaths 1 mm. thick (Fig. 2). The cadmium, possessing resonance levels around 1 eV, absorbs the incident thermal neutrons whilst the paraffin brings the direct neutrons which traverse the cadmium to energies at which their effect on the silver is most marked. Each counter was coupled to a mechanical recorder through a scale of eight possessing a resolving time of less than 2 microseconds.

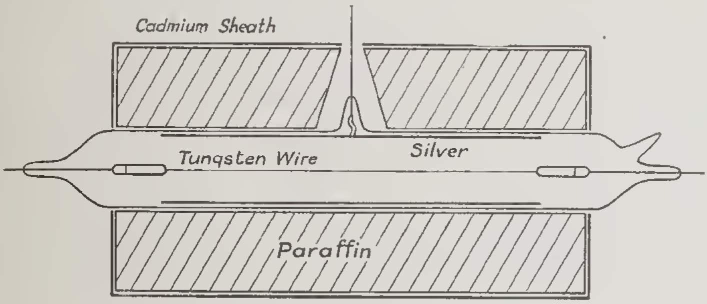

Fig. 2.

Experiments on the effect of varying the amount of cooling material (originally alcohol and dry ice) around the target indicated a marked dependence of directional yield on this quantity. Accordingly the target was arranged so that as little material as possible lay between the target and detector for the 0° and 90° positions (Fig. 3). With such an arrangement it was possible to cool the target with powdered dry ice alone and avoid the presence of the alcohol—a strong scatterer.

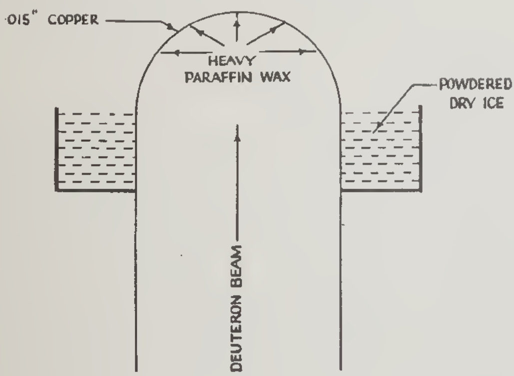

Fig. 3.

It can be shown that to a first approximation

$$\frac{\Omega_{90}}{\Omega_0} = 1 + \frac{9}{8} \cdot \frac{a^2}{l^2}$$

where Ω_{90} and Ω_0 are the average solid angles subtended by the detector of diameter, 2a, at the target when distant, l, from it. The values of l and a used in the experiment gave a maximum difference between Ω_{90} and Ω_0 of 0·7%, thus variation of solid angle subtended by the detector at the target introduced negligible errors into the results. The angular definition of the beam was 10° at the closest position to the target.

The background due to scattered neutrons was determined by the inverse square method. This involved taking observations at three neighbouring points for each direction and assuming that the background intensity was constant over the range of these points. The plotting of the measured ratios against the quantity $1/l^2$ (l being the distance between target and detector) should give a straight line, the gradient of which gives the true ratio at unit distance from the target, whilst the intercept on the ratio axis gives the background contribution to the ratio. Early measurements of background gave values around 50% of the total intensity. Such magnitudes greatly limited the accuracy of the final results and it was necessary to reduce the sensitivity of the detector to these scattered neutrons. This was achieved by enclosing the detector in an 11 cm. thick paraffin dome with an aperture left in the direction of the direct beam, (Fig. 4), an arrangement which reduced all scattered neutrons, except those coming from the target direction, to energies at which they were absorbed by the cadmium. A boron shield was placed around the cadmium to further absorb these slow neutrons. This arrangement reduced the background to the order of 10%.

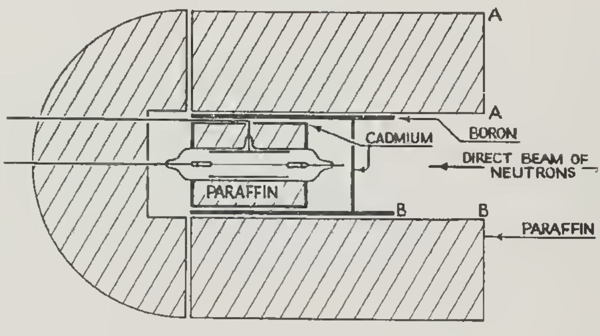

Fig. 4.

Determinations of background involve the evaluation of the distance from the target to the base of the cone of radiation detected. For the counter alone this distance could be taken to the end of the counter nearest the neutron source. However, with the counter set back inside the paraffin dome, in addition to the neutrons falling directly on the counter face, neutrons with considerable velocities could reach the counter after scattering from the annular dome end (AA), or from the inner wall (BB), and calculations gave the base of the cone of radiation detected as lying close to the front face of the dome. Since measuring the distance to the dome face altered only the magnitude of the background and had an inappreciable effect on the value of A, this practice was adopted throughout the experiment.

The procedure adopted in the experiment was to activate the counters for half a minute, count for half a minute, and then allow the activity to decay for three minutes before the cycle was repeated. A sufficient number of such runs was taken in each position to allow of a statistical accuracy of 2·5% in each ratio of detector counts to monitor counts. Calculations show that this ratio is unaffected by either the time of activation or the time of counting. A

30 second period of activation was selected because a longer period gave little increase in the amount of activity produced. The counting time was not extended beyond 30 seconds to ensure that the ratio of decay counts to natural counts was kept large—a necessary condition for accuracy.

Using a γ-ray source, the measured counting rates for various source-detector distances were compared with those calculated from the inverse square law, assuming that there are no losses at the slowest rate of counting. A plot of counting losses against counting rates gave a linear relation between these quantities. In the actual neutron measurements, however, the counting rate decayed exponentially over the 30 sec. interval for which counts were taken. In order to correct the total count in each 30 sec. period for the varying counting losses caused by this decay, the following relation between the observed count, N_0, and the true count, N, was used.

$$N = N_0 \, (1 + 1{\cdot}49 \, . \, 10^{-4} \, . \, N_0).$$

Results

The ratios of detector to monitor counts, at accelerating voltages of 145 and 190 kV, were determined at 0° and 90° to the incident deuteron beam; three source-detector distances being used in each position.

Figure 5 shows the plots of the ratios against $1/l^2$, l being the distance from source to detector, and the gradient of the line of closest fit, determined by the method of least squares, gives the yield in the appropriate direction.

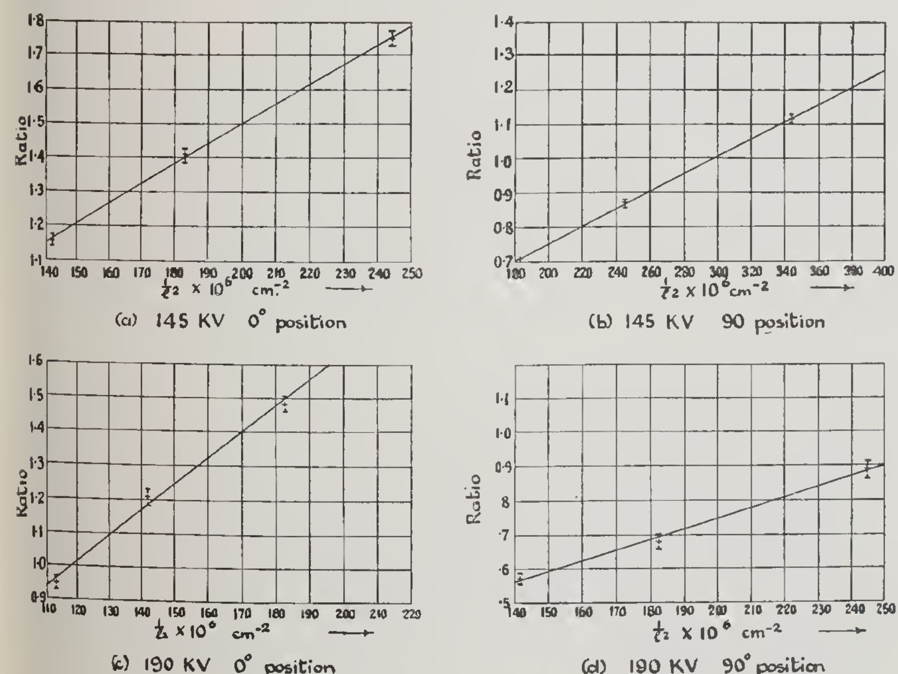

Fig. 5.

For the purpose of evaluating A at the two accelerating voltages employed an intensity distribution in centre of gravity coordinates of the form B $(1 + A\cos^2\theta')$ was assumed. The corresponding intensity distribution in room coordinates can be obtained by multiplying by the ratio of the solid angle in centre of gravity coordinates to the solid angle in room coordinates as given by:

$$\frac{\sin\theta'\,d\theta'}{\sin\theta\,d\theta} = \frac{E_d^{\frac{1}{2}}\cos\theta\,[6Q + 3E_d - E_d\sin^2\theta]^{\frac{1}{2}} + 3Q + 2E_d - E_d\sin^2\theta}{[3/2\,(Q + \frac{1}{2}E_d)\,(6Q + 3E_d - E_d\sin^2\theta)]^{\frac{1}{2}}}$$

where θ and θ' refer to the angles* in centre of gravity and room coordinates respectively,

E_d is the energy of the bombarding deuterons, and

$Q = 3{\cdot}31$ MeV.

The ratio of the intensities at 0° and 90° in room coordinates for a particular value of the accelerating voltage is a function of the constant A alone. Thus on equating this ratio to the experimental result the value of A can be determined.

To a second approximation at 145 KeV deuteron energy

$$\frac{I_0}{I_{90}} = \frac{(1 + A)\,1{\cdot}177}{(1 + 0{\cdot}0072A)\,0{\cdot}990} = 2{\cdot}26 \text{ (experimental result)}$$

giving A = 0·90 at 145 kV,

whilst at 190 kV

$$\frac{I_0}{I_{90}} = \frac{(1 + A)\,1{\cdot}200}{(1 + 0{\cdot}0093A)\,0{\cdot}996} = 2{\cdot}41 \text{ (experimental result)}$$

giving A = 1·03 at 190 kV.

The probable error in each of these results is approximately 10%. These values of A are approximately twice the magnitude of those obtained by Kempton, Browne and Maasdorp for the same voltage region and are seen from Fig. 1 to lie close to the curve of the values of A for the proton distribution obtained by Huntoon, Ellett, Bayley and Van Allen.

Since the neutron yield decreases rapidly with an accelerating voltage of less than 145 kV it has not been possible to extend the measurements to such voltages. The results obtained, however, are sufficient to show that the neutron distribution at low accelerating voltages is identical with the proton distribution.

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References

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(2) Haxby, Allen and Williams, *Phys. Rev.* **55** : 140, 1939.
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(4) Kempton, Browne and Maasdorp, *Proc. Roy. Soc. A* **157** : 386, 1936.
(5) Bennett, Mandeville and Richards, *Phys. Rev.* **69** : 418, 1946.
(6) Martin, Hill and Darby, *Proc. Roy. Soc. Vic.* **58** (N.S.) : 135, 1946.

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* The relation between θ and θ' is given by $\cos\theta' = \frac{V_n\cos\theta - \frac{1}{2}E_d^{\frac{1}{2}}}{3/2\,(Q + \frac{1}{2}E_d^{\frac{1}{2}})^{\frac{1}{2}}}$

V_n the velocity of the neutrons.